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# Historical Shoreline Changes and Their Causes,
## Texas Gulf Coast

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# HISTORICAL SHORELINE CHANGES AND THEIR CAUSES, TEXAS GULF COAST[1]

Robert A. Morton[2]

## ABSTRACT

Sequential shoreline monitoring, using vintage charts and aerial photographs, documents temporal and spatial variations in historical Gulf shoreline changes. The regional distribution of shoreline erosion and accretion largely reflects changes in littoral drift cells, decreases in sediment supply, and continuing relative sea-level rise including compactional subsidence. A Late Quaternary (circa 3500 BP) shoreline is postulated with promontories at the Holocene Brazos-Colorado and Rio Grande deltas; a third promontory along the upper coast was probably related to a Pleistocene delta system and the Sabine Arch. The interheadland areas or bights were the locations of littoral drift cells and the sites of accretionary shoreline topography primarily on barrier islands and peninsulas. Historical records (past 125 years) indicate that the deltaic headlands have experienced long-term erosion at relatively high rates. With changes in littoral drift cells, natural net shoreline accretion, supplied primarily by updrift erosion, has been generally restricted to Matagorda Island and central Padre Island in the extant zone of convergence. Short-term (past 5 to 10 years) changes are predominantly erosional with more than 70 percent of the shoreline experiencing land losses totaling about 400 acres annually.

Shoreline erosion is caused by the complex interaction of climate, sediment budget, coastal processes, relative sea-level conditions, and human activities. Jettied inlets and navigation channels serve as the greatest sediment sink, and in certain areas major shoreline changes are clearly the result of human alterations. Rates of erosion and the total length of eroding shoreline have increased during historical time. Present data indicate that most of the Texas Coast will continue to retreat landward as part of a long-term erosional trend.

## INTRODUCTION

Shoreline changes along open coasts of the world have been the subject of numerous investigations during the past two decades. Earlier studies were generally descriptive with limited quantitative data whereas recent shoreline studies include greater detail, are more comprehensive, and commonly are directed towards buyers of coastal property. There has been increased awareness and concern for shoreline changes owing to the tremendous increase in coastal development and, consequently, the utilization of land impacted by various natural hazards. In 1973, the Texas Legislature mandated the Bureau of Economic Geology to conduct historical monitoring of the entire 367 miles of Texas Gulf shoreline. Results from that study have been published by Morton (1974, 1975); Morton and Pieper (1975a, 1975b, 1976, 1977a, 1977b); and Morton and others (1976). This paper summarizes the salient facts and conclusions of that study, but important additional data document areal shoreline changes whereas only linear distances were previously reported. Estimates of areal changes provide another means of quantifying shoreline stability and determining areas of critical erosion. They also provide a basis for calculating volumetric sediment changes. Moreover, they have the potential advantage of being translated to gains and losses in real property.

Past studies of shoreline changes on the Texas Coast (Table 1) can be characterized as (1) broadly generalized regional inventories either lacking or with limited quantitative data on sequential changes and (2) more local studies of limited scope and/or duration. By contrast, the present study represents the most comprehensive and up-to-date regional study of Gulf shoreline changes.

[1]Publication authorized by the Director, Bureau of Economic Geology, The University of Texas at Austin.

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### Quantitative Methods

Descriptions of methods and limitations reported by Morton (1974) are summarized as follows. Near-vertical aerial photographs and mosaics and topographic charts were used to determine shoreline changes. Shoreline position prior to the early 1930's was established by the U.S. Coast Survey dating from 1850 but sediment-water inter-

TABLE 1
References to and previous studies of shoreline changes along the Texas Gulf Coast

| | |
|---|---|
| El-Ashry, 1966 | Some of Texas coast |
| Feray, 1963 | Rollover Pass |
| Hansen, 1960 | Mansfield Channel |
| Herbich and Hales, 1970 | San Luis Pass |
| Hunter and others, 1972 | North and central Padre Island |
| LeBlanc and Hodgson, 1959 | Entire Texas Coast |
| Mason and Sorensen, 1971 | Brown Cedar Cut |
| McGowen and Brewton, 1975 | Matagorda Peninsula |
| Piety, 1972 | Brown Cedar Cut |
| Prather and Sorensen, 1972 | Rollover Pass |
| Sealey and Ahr, 1975 | Sargent Beach |
| Seelig and Sorensen, 1973a, b | Entire Texas Coast |
| Sheets, 1947 | Near High Island |
| Shepard and Wanless, 1971 | Some of Texas Coast |
| U.S. Army Corps of Engineers, 1934 | Galveston Island |
| U.S. Army Corps of Engineers, 1953 | Galveston Island |
| U.S. Army Corps of Engineers, 1958 | Mansfield Channel |
| U.S. Army Corps of Engineers, 1959 | Rollover Pass |
| U.S. Army Corps of Engineers, 1968-74 | Entire Texas coast |
| U.S. Army Corps of Engineers, 1971a | Entire Texas coast |
| Watson and Behrens, 1976 | Corpus Christi Pass |

face mapped on aerial photographs served as an indicator of shoreline position between 1930 and 1975. Mapped shorelines were optically transferred onto common base maps (U.S. Geological Survey, 1:24,000) and direct comparisons and measurements were subsequently made.

Data from the mapped sequential changes were reduced by dividing the shoreline into 5,000-foot segments. Areas between consecutive shorelines were planimetered three times and an average of these three values was used to calculate areal changes (Table 2). Overall net changes were determined just as they were for individual time periods. Using the earliest shoreline as a base line, the comparison is equal to the areal difference between the earliest and latest shorelines. Estimates of overall net changes can also be determined by the arithmetic sum of net changes for each time period. This method is less precise because it contains additional errors from rounding off calculations. Because the arithmetic sum of net changes for each time period and the planimetered net areas should yield the same value, the difference is an estimate of overall error. For example, the sum of net changes for the first segment is -3,125 acres, whereas the planimetered net areal change is -3,131 acres (Table 2). The difference between these values is a small percentage of the total number of acres, however, all segments do not show the same degree of accuracy. Considering that nearly 6000 measurements and calculations were made, the overall error is generally small and, therefore, the data are assumed to be reasonable approximations.

## SHORELINE CHANGES

### Late Quaternary

It is important to establish late Quaternary shoreline changes along the Texas coast so that significant changes in long-term trends can be recognized and so that historical changes can be placed in proper perspective. A general description of Quaternary shoreline evolution and development of the Texas coast was presented by LeBlanc and Hodgson (1959). Radiocarbon dates and interpretations of shoreline development have also been reported for the upper coast (Gould and McFarlan, 1959; Nelson and Bray, 1970), for Galveston Island (Bernard and others, 1959), for the central coast (Shepard, 1956; Wilkinson, 1975; Wilkinson and others, 1975), for Padre Island (Fisk, 1959; Dickinson and others, 1972), and for the Rio Grande delta (Lohse, 1958).

What emerges from these data and interpretations appears to be a complex, confusing and sometimes contradictory sequence of events. Nevertheless, a generalized, if not specific, picture of the development of the Texas Coast can be described. The regional geologic framework consists of three alluvial-deltaic plains bordering the Gulf of Mexico and the barrier islands and peninsulas that occupy the bights or embayments, (Fig. 1). Two of the deltaic plains are associated with Holocene fluvial-deltaic systems (Brazos-Colorado and Rio Grande) that were active and probably prograded considerably seaward of their present positions. The third deltaic plain is an ancestral feature related to the Sabine Arch and a fluvial-deltaic system that was active along the upper Texas Coast during the Late Pleistocene.

Lohse (1958) discussed the recent history of the Rio Grande delta and concluded that during construction the shoreline prograded seaward of its present position. This is supported not only by outcrops of mud and poorly consolidated sandstone in the swash zone of south Padre Island, but also by outcrops of stiff, root mottled mud and caliche nodules obtained in sediment samples from the inner continental shelf. Moreover, point-bar accretion and sinuosity of abandoned meanders near the shoreline suggest that the lower delta plain distributary system has been transgressed. Similarly, (1) mud outcrops along Sargent Beach and the thin veneer of sand underlying Follets Island, (2) relict delta plain deposits on the inner continental shelf and, (3) point bar accretion and high-sinuosity abandoned meanders along Caney and Oyster Creeks also provide supporting evidence for a more seaward position of the Holocene Brazos-Colorado delta.

Neither the time nor the location of maximum seaward extent of either the Brazos-Colorado or Rio Grande deltas are known. Furthermore it is not known when the destructive phases of these abandoned deltas were initiated. Sediment discharge was probably greater during the Holocene, but most Texas streams were in the process of filling their estuaries and were not contributing significant quantities of sand to the littoral currents. However, the combined Brazos and Colorado Rivers and the Rio Grande River debouched directly into the Gulf, therefore contributing substantially to the sediment budget.

If the prevailing wind pattern has remained relatively unchanged during the past few thousand years, then wave refraction would have produced cells of littoral-drift convergence between the deltaic headlands. This coastal configuration and resultant areas of erosion and deposition agree with the conceptual model of littoral-power gradient proposed by May and Tanner (1973). Wave energy concentrated at the promontories in conjunction with decreased riverine sediment supply and compactional subsidence have resulted in continued headland erosion and alterations in littoral drift directions owing to reorientation of the shoreline (Fig. 2).

Although much of the evidence for previous shoreline positions in deltaic areas has been destroyed through erosion, the distribution of surface sediment on the inner continental shelf provides clues to the interpretation of relict shoreline positions. The opposite holds true for the embayed shorelines which commonly exhibit prominent ridge-and-swale topography that delineates shorelines during incipient stages of barrier development. This accretionary topography, which documents seaward advances following sea-level stillstand, is found at Sabine Pass, on Bolivar Peninsula, and on Galveston, Matagorda and San Jose Islands. The postulated shoreline positions and locations of littoral-drift cells imply that low and narrow barrier segments such as Follets Island, Matagorda Peninsula, and South Padre Island are relatively young geomorphic features. Also they imply that longshore currents transported additional sediment to interdeltaic areas, but Tanner (1973) stated that the long, linear ridge and swale topography parallel to the present day shoreline indicates that shoreline accretion was supplied largely by onshore transport from sediment sources on the inner continental shelf. This interpretation is supported by Van Andel and Poole (1960) and Shepard (1960) who suggested that sediments of the Texas Coast are largely of local origin. From the spatial relationships of the Ingleside sand and the extant barrier islands, McGowen and others (1972) also concluded that the primary source of sediment for modern sand-rich barriers

Table 2. Planimetered areas of seqential gains and losses between 1850-83 and 1973-75- areas in acres.

| Coastal Segment | | | | | | Net Change |
|---|---|---|---|---|---|---|
| | Time | 1882-83 to 1930-33 | 1930-33 to 1955-57 | 1955-57 to 1965 | 1965 to 1974 | 1882-83 to 1974 |
| Sabine Pass | Erosion | -2136 | -988 | -760 | -609 | -3601 |
| to | Accretion | +625 | +679 | +42 | +22 | +470 |
| Bolivar Roads | Net change | -1511 | -309 | -718 | -587 | -3131 |
| | Time | 1850-52 to 1930 | 1930 to 1956 | 1956 to 1965-70 | 1965-70 to 1973-74 | 1850-52 to 1973-74 |
| Bolivar Roads | Erosion | -889 | -100 | -485 | -270 | -1183 |
| to | Accretion | +912 | +668 | +22 | +12 | +1074 |
| San Luis Pass | Net change | +23 | +568 | -463 | -258 | -109 |
| | Time | 1850-56 to 1930-37 | 1930-37 to 1956-57 | 1956-57 to 1965 | 1965 to 1974 | 1850-56 to 1974 |
| San Luis Pass | Erosion | -2031 | -2327 | -793 | -928 | -4119 |
| to | Accretion | +1789 | +2722 | +285 | +336 | +3373 |
| Brown Cedar Cut | Net change | -242 | +395 | -508 | -592 | -746 |
| | Time | 1855-57 to 1937 | 1937 to 1956-57 | 1956-57 to 1965 | 1965 to 1974 | 1855-57 to 1974 |
| Brown Cedar Cut | Erosion | -1271 | -719 | -545 | -811 | -2740 |
| to | Accretion | +210 | +84 | +265 | +140 | +96 |
| Pass Cavallo | Net change | -1061 | -635 | -280 | -671 | -2644 |
| | Time | 1857-60 to 1937 | 1937 to 1957 | 1957 to 1965 | 1965 to 1974 | 1857-60 to 1974 |
| Pass Cavallo | Erosion | -464 | -423 | -892 | -426 | -890 |
| to | Accretion | +1900 | +361 | +21 | +21 | +1108 |
| Cedar Bayou | Net change | +1436 | -62 | -871 | -405 | +218 |
| | Time | 1860-62 to 1931-37 | 1931-37 to 1957-58 | 1957-58 to 1965 | 1965 to 1974 | 1860-62 to 1974 |
| Cedar Bayou | Erosion | -22 | -118 | -232 | -144 | -99 |
| to | Accretion | +449 | +39 | +22 | +33 | +110 |
| Aransas Pass | Net change | +427 | -79 | -210 | -111 | +11 |
| | Time | 1860-82 to 1937 | 1937 to 1958-60 | 1958-60 to 1969-70 | 1969-70 to 1974-75 | 1860-82 to 1974-75 |
| Aransas Pass | Erosion | -254 | -198 | -209 | -696 | -776 |
| to | Accretion | +617 | +260 | +341 | +45 | +538 |
| Yarborough Pass | Net change | +363 | +62 | +132 | -651 | -238 |
| | Time | 1879-82 to 1937 | 1937 to 1960 | 1960 to 1969 | 1969 to 1975 | 1879-82 to 1975 |
| Yarborough Pass | Erosion | -25 | -393 | -326 | -402 | -472 |
| to | Accretion | +910 | +244 | +45 | +10 | +489 |
| Mansfield Channel | Net change | +885 | -149 | -281 | -392 | +17 |
| | Time | 1867-80 to 1937 | 1937 to 1960 | 1960 to 1969 | 1969 to 1974-75 | 1867-80 to 1974-75 |
| Mansfield Channel | Erosion | -2357 | -838 | -599 | -398 | -3878 |
| to | Accretion | +292 | +50 | +22 | +17 | +274 |
| Rio Grande | Net change | -2065 | -788 | -577 | -381 | -3604 |
| TOTAL NET CHANGE | | -1745 | -997 | -3776 | -4048 | -10226 |

was local Pleistocene and early Holocene deposits on the inner shelf.

Initial shoreline progradation was rapid because of abundant sediment supply and shallow water depths, but the volume of sediment required for continued shoreline accretion was greatly increased by progradation into deeper water. At some time, the shelf sediment supply was essentially depleted. During the past several hundred years the deltaic headlands have continued to erode, but conditions that promoted seaward accretion in the bights have been altered both naturally and, more recently, by man. Consequently sediment supply to the Texas coast has diminished and erosion is prevalent.

## Historical Shoreline Changes

1850-83 to 1930-37

Coastwise areal shoreline changes between the mid to late 1800's and the 1930's (Table 2) were diverse, but the regional distribution (Fig. 3) was similar to the inferred prehistoric shoreline changes. Major losses were experienced from west of Sabine Pass to Rollover Pass, along Follets Island, Sargent Beach, and most of Matagorda

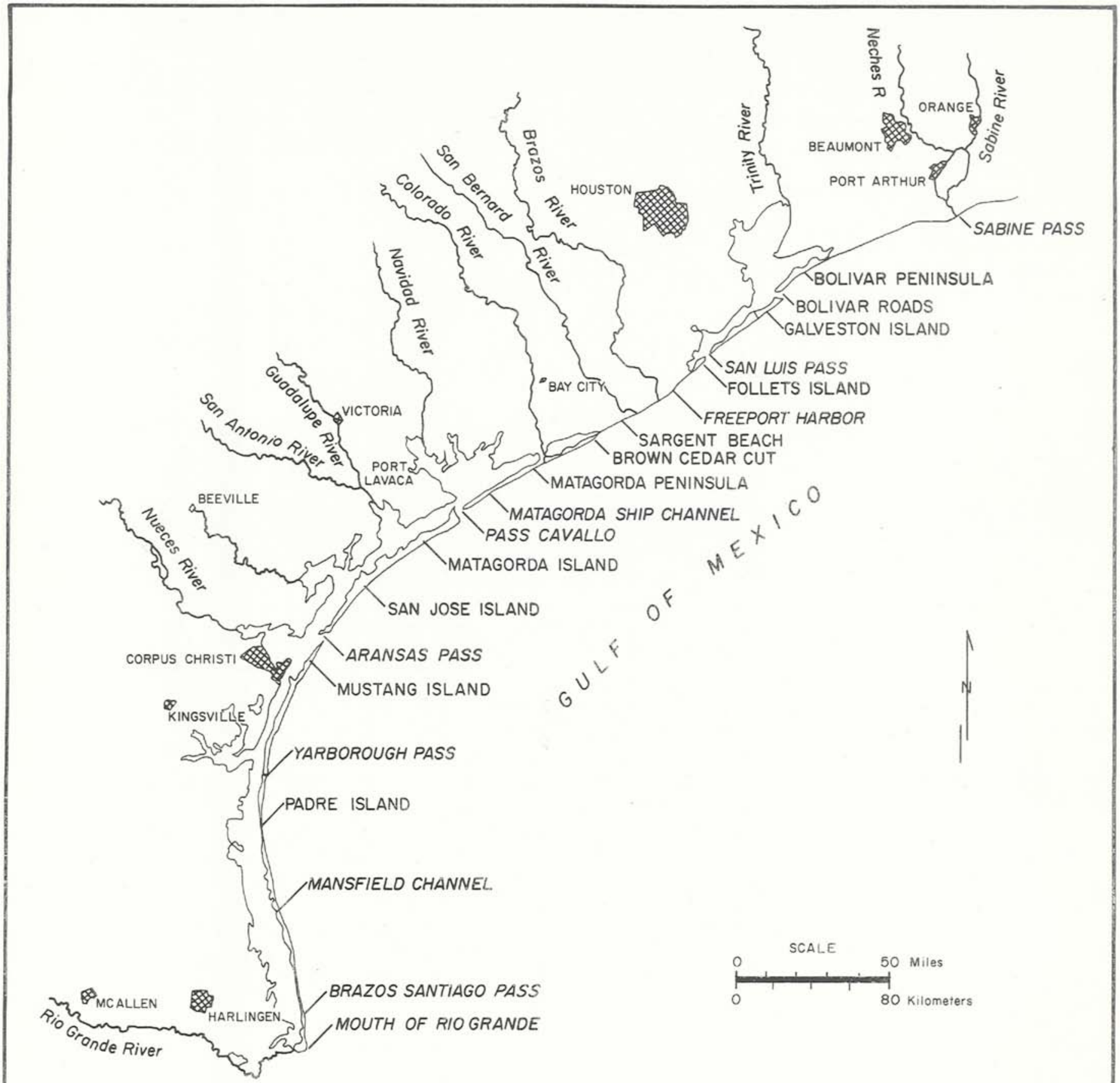


**FIGURE 1.** Index map of the Texas Gulf shoreline.

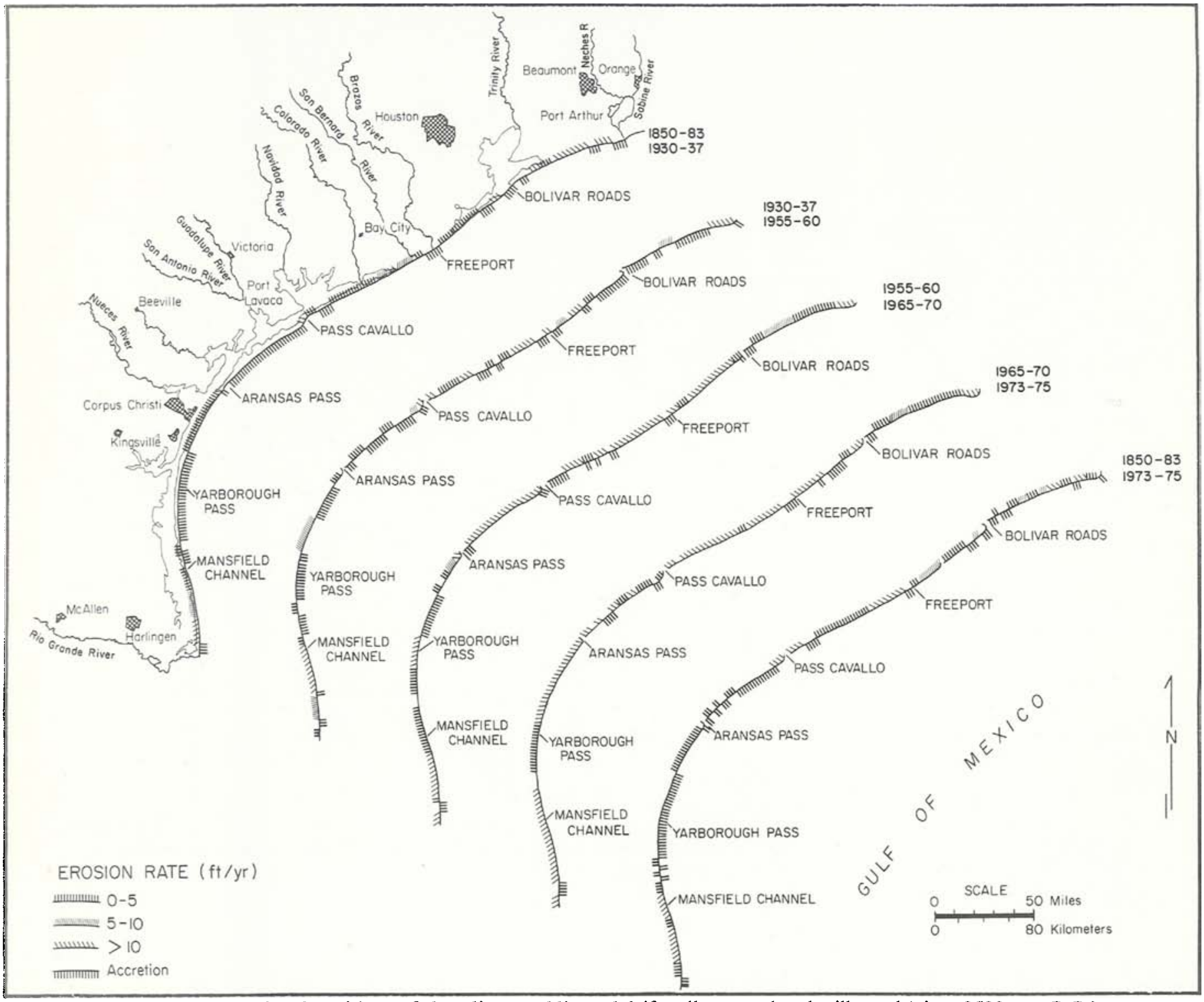


**FIGURE 2.** Postulated positions of shorelines and littoral drift cells at sea-level stillstand (circa 3500 yrs. B.P.) with inferred shoreline changes. Extant littoral drift convergence after Watson (1968).

Peninsula, and along south Padre Island. The greatest gains occurred on Matagorda Island (1436 acres) and south of Yarborough Pass (885 acres), but substantial gains were also recorded on San Jose Island (427 acres) as well as on Mustang and north Padre Islands (363 acres).

Total net losses were approximately 1745 acres, but even greater losses would be recorded if the substantial gains attributed to human alterations were discounted. Channels were deepened and jetties were constructed at the Brazos River and at major tidal inlets (Sabine Pass, Bolivar Roads, Aransas Pass, Brazos-Santiago Pass) in order to provide deeper and more stable navigation channels. Shoreline accretion attendant with these modifications represents an appreciable, although local, gain in acres. For example, 376 acres accreted adjacent to the west jetty at Sabine Pass while 766 acres accreted updrift and downdrift of Bolivar Roads. At about the same time, nearly 1790 acres accreted on both sides of the jetties at Freeport Harbor. Such large accumulations demonstrate and emphasize the marked effect of these coastal structures on shoreline changes.

1930-37 to 1955-60

Shoreline erosion was common during this time period. Except for anamolously high accretion on the upper coast (Fig. 3) and exceptionally large gains associated with diversion of the Brazos River and subsequent development of the new Brazos delta, net losses occurred along the same segments as during the preceding time interval. But more important were the reversals from net accretion to net erosion on Matagorda, San Jose, and central Padre Islands (Table 2). These reversals marked the beginning of long-term erosional trends for each of these coastal segments. The shoreline between Aransas Pass and Yarborough Pass continued to accrete, but net accretion was minor.

Erosion claimed nearly a thousand acres between 1930-37 and 1955-60 and even greater losses would be

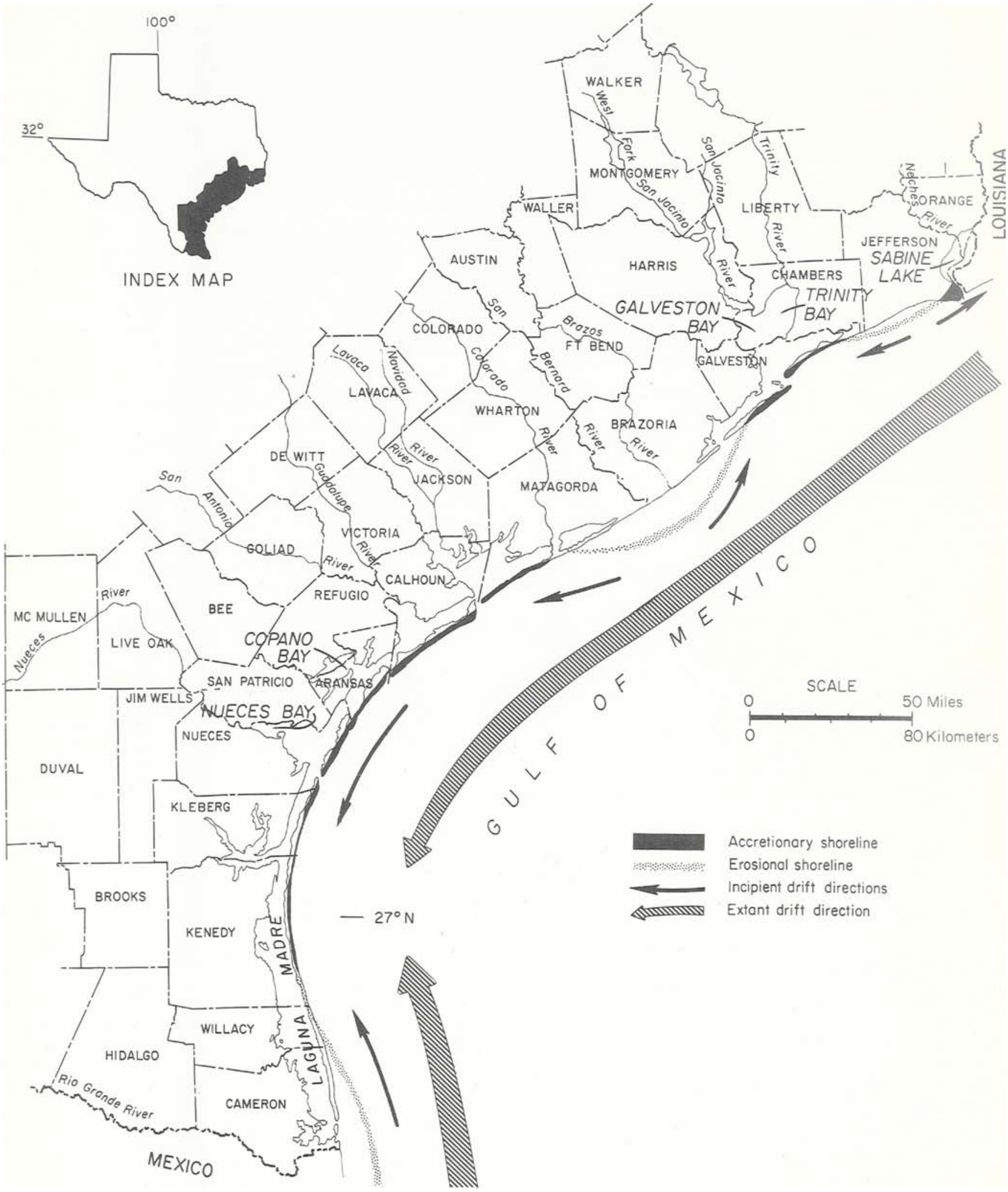


**FIGURE 3.** Sequential and net shoreline changes from 1850-83 to 1973-75, Texas Gulf shoreline.

recorded if the tremendous gains from the new Brazos delta (over 2300 acres) and continued accretion at Bolivar Roads (332 acres) were eliminated. Shoreline accretion associated with other coastal structures was minor and the trend was dominantly erosional at Sabine Pass and Freeport Harbor.

1955-60 to 1965-70

For the first time since the 1800's, shoreline changes were clearly erosional for all but one of the coastal segments. Even though net gains were recorded between Aransas Pass and Yarborough Pass (Table 2), there is reason to suspect that data for this particular segment are misleading as explained elsewhere. Total net losses exceeded 3700 acres, Matagorda Island suffered the greatest losses but substantial losses also were recorded on the upper coast and along south Padre Island. By this time shoreline changes attendant with human modifications at navigation channels were minimal. Even the conditions at the mouth of the new Brazos River did not overshadow the losses along Follets Island, Sargent Beach, and in the vicinity of Freeport. The least amount of land was lost between Cedar Bayou and Mansfield channel which suggests relative shoreline stability as compared to other coastal segments.

1965-70 to 1973-75

Between 1965-70 and 1973-75 over 4000 acres of Gulf front property were lost from the Texas coast (Table 2) at an alarming rate. All segments recorded net losses (Fig. 3), but the distribution of losses was surprisingly uniform. Greatest losses were along Matagorda Peninsula but the most significant losses occurred from Aransas Pass to Yarborough Pass, a segment that had apparently experienced accretion throughout the previous time periods. Unfortunately, an undetermined proportion of these losses can be attributed to complications with the original data. Morton and Pieper (1977a) described how the low tidal stage on 1970 photography caused an apparent reduction in erosion or increase in accretion for this particular segment during the preceding time period and subsequent increases in erosion and reduction of accretion during the following time period

Perhaps some minor adjustments should be made to compensate for the error introduced by differences in tidal stage. If some of the losses recorded between 1969-70 and 1974-75 actually occurred between 1958-60 and 1969-70, then the net change for the latter time period would probably shift from accretion to erosion and the last two time periods would be characterized by net losses for all coastal segments. Such minor adjustments would effect net changes for this particular segment (Aransas Pass to Yarborough Pass) but would not significantly alter the total net change for either time interval.

1850-83 to 1973-75

In many ways the net overall changes are a reflection of the trends established between the mid to late 1800's and the 1930's, but recent increases in erosion (Table 2) have either substantially reduced net gains or greatly increased net losses by comparison to the first time period. Erosion has permanently removed slightly more than 10,000 acres from the Texas Coast since the mid to late 1800's. Major net losses occurred from Sabine Pass to Bolivar Roads, along Matagorda Peninsula, and along south Padre Island whereas the shoreline experienced minor gains and losses or remained relatively stable between Pass Cavallo and Mansfield Channel.

Perhaps even more important is the rate at which the losses have occurred. Calculations based on total net changes and average number of years for each time interval suggest that the rates of net losses have increased for each consecutive time interval. Although this may be in part, a function of decreasing time interval, the magnitude of the rate increases suggest that the trend is real and should be of special concern.

## NET ACCRETION

The question of temporal and spatial changes in sediment budget will be addressed in a following section, but specific instances of natural and man induced accretion require further explanation because of their importance in understanding the sediment sources and physical processes that cause such changes. The three special cases discussed here are accretion (1) at the new Brazos delta, (2) at jettied inlets, and (3) in the vicinity of Yarborough Pass.

Progradation of the new Brazos delta appears to be an enigma because the old Brazos River was unable to construct a substantial delta (U.S. Army Corps Engineers, 1853-54) prior to river mouth alterations and jetty construction. Sediment for the new Brazos delta was derived primarily from: (1) fluvial sediment transport; (2) bank and bed erosion during adjustment of the diversion channel; (3) erosion of the old Brazos delta; and (4) trapping of the littoral drift. When dredged, the cross section along most of the diversion channel was about one-third that of the Brazos River channel (Fox, 1931). The volume of sediment contributed during adjustment of the diversion channel is unknown but it probably was subordinate to the sediment supplied by destruction of the old Brazos delta. Wave refraction around the new delta created counter currents that intercepted and caused deposition of the littoral drift normally transported along the coast. This probably was the greatest additional source of sediment, but it may have become increasingly more important through a feedback mechanism as the delta prograded. With westerly migration of the delta and increased erosion on the eastern (Bryan Beach) side it is apparent that sediment supplied by channel adjustment and updrift shoreline erosion have noticeably decreased.

Although human modifications and associated shoreline changes at other navigation channels have not been quite as dramatic, they do represent a significant proportion of relatively permanent gains. At their maximum extent, the updrift and downdrift accretion at Sabine Pass, Bolivar Roads, Aransas Pass, and Brazos Santiago Pass accounted for nearly 1900 acres. Major gains were made during the time period following construction, but shoreline accretion progressively decreased and at most of the older jettied inlets the shorelines have stabilized or begun to erode. The shorelines updrift from Matagorda Ship Channel and Mansfield Channel continue to accrete primarily because these alterations are relatively new and equilibrium conditions have not been reached.

Shoreline accretion at jettied inlets has commonly been attributed to impoundment of littoral drift. This appears to be true in most cases, but what has not been generally recognized is that sediment can be supplied from the shoreface by changes in the offshore profile. Human alterations at natural inlets commonly caused bathymetric adjustments and redistribution of ebb-tidal deltas in response to shoreface erosion and landward sediment transport. During historical time sediment discharge from major rivers has diminished and it appears that net accretion at most jettied inlets has been supplied by shoreline and shoreface erosion.

Net gains in the vicinity of Yarborough Pass are another example of shoreline accretion supplied by updrift erosion. For the most part, subdivision of the Texas coast at natural inlets and man-made channels was adequate for describing shoreline changes. But the long-term accretion extending about 10 miles on either side of Yarborough Pass is masked by dominantly erosional trends north and south of this area. Although the net gain on central Padre Island of nearly 800 acres represents less than 10 percent of the total net losses, the gains are significant in documentating net accretion in the zone of littoral drift convergence. The combination of basin configuration and shoreline orientation plus predominant wind direction produces southwesterly littoral drift along the upper and central Texas Coast (Fig. 2), whereas, littoral drift is northerly along the lower coast (Sweitzer, 1898; Lohse, 1955). Apparently, the zone of convergence is located near 27°N latitude (Watson, 1968), but seasonal conditions cause the convergence to shift up the coast toward north Padre Island (Curray, 1960). The shoreline segment exhibiting long-term net accretion nearly coincides with the transition zones established by heavy minerals, grain size distributions and shell species (Bullard, 1942; Van Andel and Poole, 1960; Hayes, 1965; and Watson, 1968). The only difference is that net shoreline accretion extends northward beyond Yarborough Pass.

Net shoreline changes on central Padre Island support the conclusions of Bullard (1942) and Watson (1968) regarding directions of longshore drift and the location of net drift convergence. Furthermore, they refute the interpretation of Van Andel and Poole (1960) who concluded that local shelf sediments were the single source of barrier island sand along this coastal segment. Clearly, longshore drift (shoreline erosion and fluvial sediment) as well as landward transport of reworked shelf sediment were important intrabasin sources of barrier island sand in this area.

## CONTRIBUTING FACTORS

It is difficult, if not impossible, to isolate and quantify all the specific factors causing shoreline changes (Fig. 4). But, in order to evaluate the various factors and their interrelationships, it is necessary to discuss not only major factors but also minor factors. The basis for future prediction comes from this evaluation.

### Climate

Climatic changes during the past 18,000 years have been documented by various methods. In general, temperature was lower (Flint, 1957) and precipitation was greater (Schumm, 1965) at the end of the Pleistocene than at present; the warmer and drier conditions which now prevail control other factors such as vegetal cover, runoff, sediment concentration, and sediment yield.

Dury (1965) estimated that discharge for many early Holocene rivers was 5 to 10 times greater than for the same present-day rivers. Observations based on geologic maps prepared by the Bureau of Economic Geology (Fisher and others, 1972) confirm that many rivers along the Texas Coastal Plain were larger and probably transported greater volumes of sediment during the early Holocene. This, in turn, affected sediment budget by supplying additional sediment to the littoral drift system.

Droughts may be a potential though indirect factor related to shoreline changes via their adverse effect on vegetation and their influence on relative sea-level conditions. Because dunes and beach sand are stabilized by vegetation, sparse vegetation resulting from droughts (1) offers less resistence to wave attack and (2) promotes removal of sand from beaches by eolian processes.

### Storm Frequency and Intensity

Storms are not the only coastal process responsible for shoreline changes, but they do represent the most concentrated energy sources and they are responsible for the greatest short-term changes and perhaps much of the long-term changes. The frequency of tropical cyclones is dependent, in part, on cyclic fluctuations in temperature; hurricane frequency increases during warm cycles (Dunn and Miller, 1964). According to summaries based on records of the U.S. Weather Bureau (Tannehill, 1956; Dunn and Miller, 1964; Cry, 1965), some 62 tropical cyclones have either struck or affected the Texas Coast during this century (1900-1976). The average of 0.8 hurricane per year obtained from these data is similar to the 0.67 per year average reported by Hayes (1967).

High velocity winds with attendant waves and currents of destructive force scour and transport large quantities of sand during hurricane approach and landfall. Damage to the beach and adjacent areas depends on a number of factors including angle of storm approach, configuration of the shoreline, shape and slope of Gulf bottom, wind velocity, forward speed of the storm, distance from the eye, stage of astronomical tide, decrease in atmospheric pressure, and longevity of the storm. Comparisons of some of the more recent hurricanes that affected Texas beaches were provided by Hayes (1967) and McGowen and others (1970). Individual studies of Hurricanes Carla (1961), Beulah (1967), Celia (1970), and Fern (1971) were conducted by the U.S. Army Corps of Engineers (1962, 1968, 1971b, 1972). Adjustments of shorelines, vegetation lines, and beach profiles during and after storms were discussed by Morton (1974) who also described hurricane destruction along a developed coastline (Morton, 1976).

### Relative Sea-Level

Relative sea-level changes are important because a minor vertical rise in sea level relative to low-lying coastal areas can cause considerable landward displacement of the shoreline. Of the four factors relevant to land-sea relationships (Fig. 4) only two factors are of major importance along the Texas Coast. Tectonic forces may be important in some coastal areas, but in general, sediment supply along the Texas coast has far exceeded tectonic subsidence. There are some indications, however, that tectonic subsidence may be less over the San Marcos Arch, possibly contributing to greater shoreline stability along the central coast. Eustatic sea-level rise has been documented (Lisitzin, 1973) but it is probably a minor factor along the Gulf Coast not only because it is difficult to define (Moerner, 1976) but also because compactional subsidence and secular sea-level variations are of greater magnitude.

Holocene sea-level changes are based on $C^{14}$ data, but

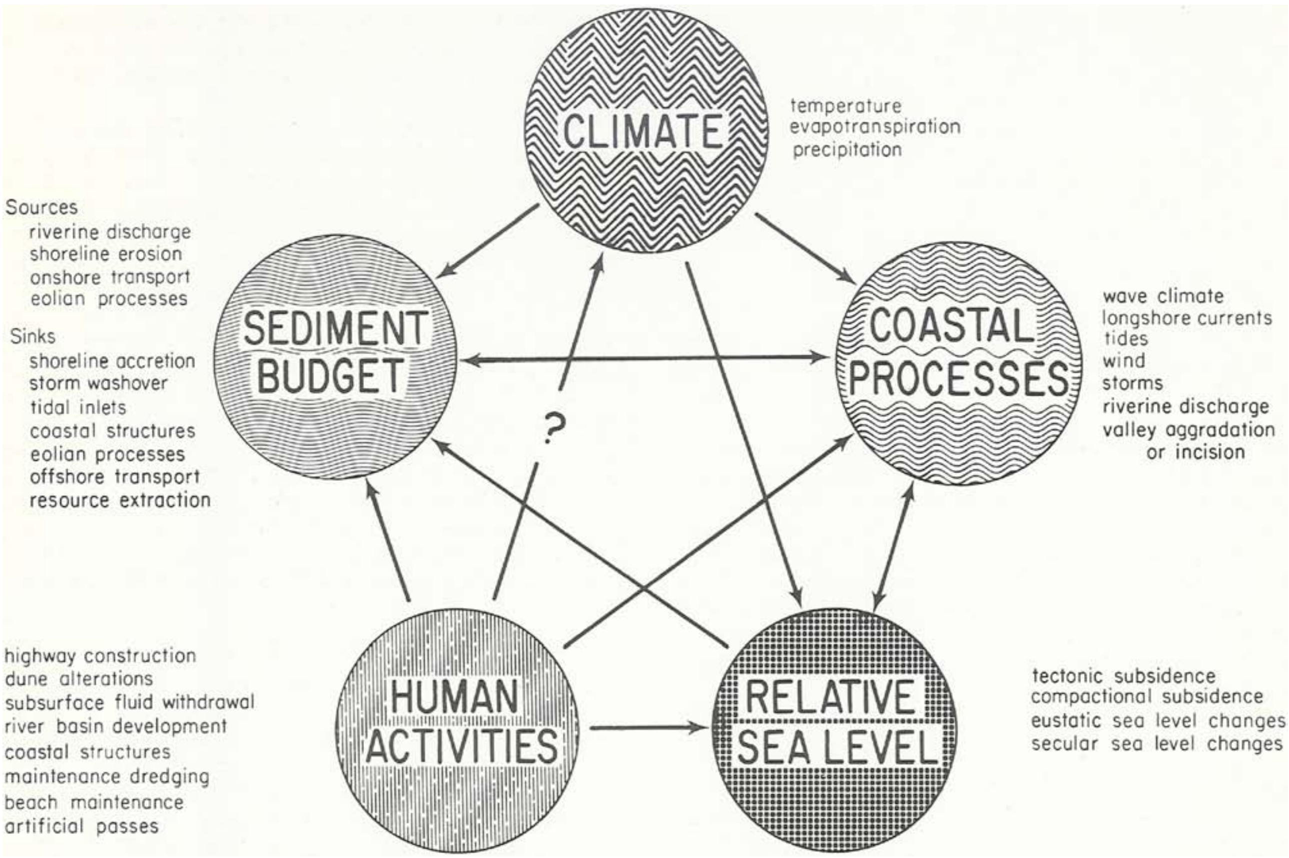


**FIGURE 4.** Interaction of factors affecting shoreline changes. Arrows point towards the dependent variables; the number of arrows originating from or terminating at a particular factor indicates the relative degree of independence or interaction. For example, human activities are independent of the other factors, but they affect sediment budget, coastal processes, relative sea-level conditions, and, perhaps, climate.

relative sea-level changes during historical time (Fig. 5) are deduced by monitoring mean sea level and developing trends based on long-term measurements (Gutenberg, 1941; Marmer, 1951; Hicks, 1972). However, this method does not distinguish between sea-level rise and land-surface subsidence. Because of this limitation, Swanson and Thurlow (1973) used statistical methods to correct tidal data for the glacial-eustatic component and they concluded that the relative rise in sea level along the Texas coast was due to compactional subsidence.

There is increasing concern regarding land-surface subsidence associated with production of oil (Pratt and Johnson, 1926) and withdrawal of ground water (Gabrysch, 1969). Land surface subsidence from fluid withdrawal appears to be minor in most areas (Brown and others, 1974) but continued withdrawal and concomitant decline in fluid pressure could eventually cause additional decreases in surface elevation. Such would augment the effects of compactional subsidence and lead to future loss of land, especially where large volumes of ground water or hydrocarbons are produced at or near the shoreline.

Secular sea-level variations, or time dependent oscillations superimposed on the general upward trend in sea level (Hicks and Crosby, 1975) may also be important causes of shoreline changes, particularly short-term changes. For example, anomalous shoreline accretion along portions of the upper and central coast during the mid 1950's are probably related to a lower sea level trend illustrated by many tide gage records around the United States (Hicks and Crosby, 1975; Swanson and Thurlow, 1973) including the Galveston gage (Fig. 5). Most of the State was affected by drought conditions between 1950 and 1956. The most severe drought, between 1954 and 1956 (Lowry, 1959), was manifested by reduced riverine discharge and by excessive evaporation. These conditions would cause apparent shoreline accretion by lowering the water level. Similarly, the upward trend in sea-level variations in recent years (Hicks and Crosby, 1975) may be largely responsible for increased and nearly coastwide shoreline erosion. Moreover, it appears that compactional subsidence and eustatic sea-level rise would favor continued sea level rise relative to the land surface in Texas.

## Sediment Budget

Detailed quantitative analyses of sediment sources and sinks (Fig. 4) are required in order to determine sediment budget. Such a study has not been completed and, therefore, only a qualitative assessment will be presented. Johnson (1959) discussed some major sources of sand supply and causes for sand loss along coasts that included three sources (major streams, onshore movement of shelf sand by wave action, and eolian processes) that are applicable to the Texas Coast. Cliff erosion, a fourth source listed by Johnson, is analogous to shoreline erosion. The eolian contribution is discounted because it is of short duration, occurring only during dry northers, and the total

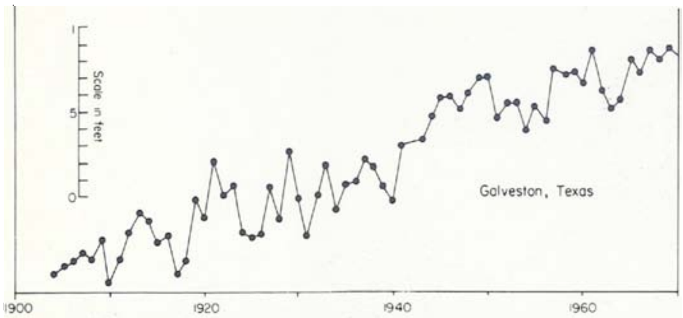

**FIGURE 5.** Relative sea-level changes based on tide gage measurements for Galveston, Texas. Data from Gutenberg (1941), Marmer (1951), and Swanson and Thurlow (1973).

volume of sand transported off the backbeach and into the surf zone is insignificant. Updrift shoreline and shoreface erosion are probably the largest extant sources of sediment, but supply estimates must be reduced because the areas of greatest shoreline erosion (near Sabine Pass, Brazos-Colorado delta, Rio Grande delta) have clay substrates which do not contribute substantial quantities of sand in relation to the area eroded.

Sediment supplied by coastal rivers was undoubtedly important in the past, but natural decreases in sediment supply and river basin development have reduced the sand supply of Texas rivers considerably. Discharge, silt load, and concomitant bed load (dominantly sand) of the Rio Grande were sharply reduced following construction of Falcon Dam (Morton and Pieper, 1975a). Reductions in sediment load have not been as great for the Brazos River (Morton and Pieper, 1975b), but reductions in peak discharge probably have caused substantial decreases in bed-load transport. The other rivers that debouch directly into the Gulf (San Bernard and Colorado) have not been significant sources of sediment during historical time because of limited drainage area and limited duration, respectively. Until 1936, the Colorado River emptied into Matagorda Bay. Since then, the river mouth has been prone to silting because of gradient disequilibrium along its lower reaches. Sediment supply has not been sufficient enough to reduce shoreline erosion at the mouth of the Colorado (Morton and others, 1976).

Landward transport of shelf sediment was also more important in the past. This source has probably diminished due to equilibration of the inner shelf profile, a development stage referred to by Tanner (1975) as maturing of the system. The major sources of sediment for barrier island development have either been depleted or have diminished by natural causes and, more recently, by human activities. Human alterations such as impermeable barriers (jetties), dredged navigation channels, and river diversion are responsible for the greatest losses of sand along the Texas Coast. Unfortunately, there are generally permanent losses from the natural system and they may contribute to additional losses in the future. The second most important sink is natural shoreline accretion. The two areas receiving the most sand were Matagorda Island and Padre Island in the zone of convergence. Past and present eolian losses are also important along Padre Island; the highest dunes and most extensive dune fields occur south of Yarborough Pass, and active dunes 10 to 20 feet high have formed since hurricane Beulah on south Padre Island. Eolian transport is also important on north Padre Island. Active blowouts and migrating dune fields as well as studies of dune growth (Otteni and others, 1972) document the removal of sand from the littoral drift system.

Sand losses listed by Johnson (1959) do not include deposition at tidal inlets and storm washovers; these are two important sinks in some areas. During storms, sand may move offshore into deeper water or into lagoons through washover channels. Storm washover and eolian losses are about equal but they account for considerably less than human alterations and shoreline accretion. Storm washover losses are generally restricted to Matagorda Peninsula, southern San Jose Island, and south Padre Island. Losses at natural tidal inlets are minor although some losses occurred with closing of smaller inlets such as Greens Bayou, Packery Channel, Boca Chica Inlet, and Yarborough Pass. Flood tidal deltas at Brown Cedar Cut and at Corpus Christi and Rollover fish passes also account for minor sediment losses. Offshore transport has not been satisfactorily evaluated, but judging from limited preliminary data, it would rank as a minor sink for sand and a major sink for silt and clay eroded from beaches.

### Human Activities

Shoreline changes induced by man are difficult to quantify because human activities promote alterations and imbalances in sediment budget, coastal processes, and relative sea-level conditions (Fig. 4). For example, construction of dams, erection of seawalls, groins, and jetties, and removal of sediment for building purposes all contribute to changes in quantity and type of beach material delivered to the Texas Coast. Even vehicular traffic and beach scraping can contribute to overall changes, although they are not controlling factors. Erection of impermeable structures and mining of sediment have immediate, as well as long-term effects, whereas a lag of several to many years may be required to evaluate fully the effect of other activities such as subsurface fluid withdrawal.

Jetties were constructed at most of the major tidal inlets along the Texas coast and artificial passes were dredged at Rollover Pass, Corpus Christi Pass, Matagorda Ship Channel, and Mansfield Channel. Projects such as these serve to alter natural processes. Their effects on shoreline changes are subject to debate, but it is an elementary fact that impermeable structures interrupt littoral drift and impoundment of sand occurs at the expense of the beach downdrift of the structures. Perhaps the clearest examples of increased erosion resulting from human alterations can be demonstrated (1) at the west end of the Galveston seawall (2) at Surfside and Quintana (Freeport Harbor) (3) at Matagorda Ship Channel and (4) at Mansfield Channel.

## ANTICIPATED FUTURE CHANGES

The available data suggest that most of the Texas Coast will continue to retreat landward as part of a long-term erosional trend. The combined influence of interrupted and decreased sediment supply, relative sea-level rise, and tropical cyclones is nearly insurmountable. There is no evidence that suggests a long-term reversal in any trends of the major causal factors. Sand stored in the barrier islands and peninsulas should help to minimize erosion and keep rates of erosion relatively low. Conversely, where clay substrates predominate, rates of erosion will probably continue to be higher.

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